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THE SUBMICROSECOND STRUCTURE OF LIGHTNING RADIATION FIELDS

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ABSTRACT

The EM fields radiated by the preliminary cloud breakdown,
leader steps, and the return strokes in cloud-to-ground lightning
all exhibit large submicrosecond variations. Values of the maximum
dE/dt during return strokes range from 7 to 76 V/m/us, when range- (microsec)
normalized to 100 km, with a mean and standard deviation of 33
(+ or – 14 V/m/microsec ± 14 V/m/us. If this return stroke field is produced by a single
current pulse propagating upward at a speed of 10^8 ms, then the (10 to the 8th microsec)
above values of dE/dt imply that the maximum dI/dt ranges from
microsec) 35 to 355 kA/us with a mean of 154 ± 70 kA/us. Leader steps just
above the ground and the fast components of large cloud pulses
produce dE/dt signatures that are often surprisingly similar to
those from return strokes.

ALTHOUGH THE INTERACTIONS of lightning with aircraft, space vehicles, power systems, ships, and other structures are critically dependent on the risetimes and the maximum rates of change of the lightning fields and currents, there are relatively few fast time-resolved measurements of these quantities in the published literature (1)*. For the past several years, the University of Arizona has been attempting to measure the E and dE/dt signatures produced by various lightning processes with submicrosecond resolution. A description of the apparatus used to make these measurements and examples of the data have been given previously by Weidman and Krider (2,3,4) and Weidman (5). Here, we will present some inferences of the maximum rates of change of the channel currents that have been derived from the E and dE/dt fields.

I. EXPERIMENT

We have endeavored to measure the E and dE/dt signatures produced by known discharge processes under conditions where the results would not be significantly affected either by the response time of the measuring equipment or by ground wave propagation. Two experiment sites were chosen where the lightning and the field propagation were over salt water so that the effects of propagation were minimal. One site was near Tampa Bay, Florida, and the other was at the NASA Kennedy Space Center, Florida. A commercial lightning locating system (6,7) provided the locations of most cloud-to-ground flashes within about 100 km of each site. The field sensors and recording equipment were placed within a few meters of the shore, again so that the field propagation would be almost entirely over salt water to the recording equipment.

E signatures were recorded on both a slow and a fast time scale so that the type of lightning impulse which produced the dE/dt signature, and the precise time within the E signature that the dE/dt occurred, could be determined. The E field measuring system had a 10 to 90% risetime of about 40 ns, and the dE/dt system had a risetime of about 10 nsec.

II. RESULTS

RETURN STROKES - In general, the shape of the electric fields radiated by a return stroke depends on whether it is the first return stroke in a flash, a subsequent return stroke, or a subsequent return stroke that is preceeded by a dart-stepped leader (2). First stroke fields begin with a relatively slow "front" which rises for 2 to 8 μs to about half of the peak field amplitude. This front is followed by a fast transition to peak, and it is this fast transition which is of primary interest in this report. Subsequent strokes produce fields that have fast transitions very similar to first strokes, but the fronts last only 0.5 to 1 μs and rise to only about 20% of the peak field amplitude.

A reproduction of the fast field transition produced by a first return stroke, and a histogram of measured 10 to 90% fast transition risetimes are given in Fig. 1. Note that the mean risetime is only 90 ns and that the standard deviation is only 40 ns.

The width of the fast initial peak produced by return strokes is surprisingly narrow. Fig. 2 summarizes the full width of this peak measured halfway between the onset of the fast transition or breakpoint and the peak (FWHM). Note that the mean and standard deviation of this width are only 360 ± 140 ns.

The maximum slopes of the fast field transitions produced by return strokes are summarized in Fig. 3. Here, all data have been range-normalized to 100 km assuming there is a simple inverse distance dependence in the amplitude of the fast transition, ΔE. The values of $\Delta E/\Delta t$ in Fig. 3 range from 7 to 76 V/m/μs, and the mean and standard deviation are 33 ± 14 V/m/μs. These data are plotted for different range intervals, and from these results we infer that the range-normalized values do not have a significant dependence on distance.

Fig. 4 shows a plot of the range-normalized values of the maximum field slope, $\Delta E/\Delta t$, versus the associated range-normalized ΔE. There is a rather large scatter in the points, but the best linear fit to these data has a slope of 9.1 μs^{-1}, and the correlation coefficient is 0.71. The implications of Figs. 3 and 4 for the maximum current derivative in return strokes will be given in the Discussion.

STEPPED-LEADER - The overall shapes of the fields radiated by individual steps of the stepped-leader have been discussed by Krider and Radda (8) and Krider, et. al. (9). As the leader nears the ground, the amplitude of individual step impulses increases, and occasionally such a step triggered our E or dE/dt recording system just before there was a return stroke. The maximum dE/dt occurs during the initial rise of the step waveform, and values of this quantity derived from the initial slopes of E data have a mean and standard deviation of 27 ± 9 V/m/μs for 18 steps. The shapes of the leader dE/dt signatures are very similar to those from return strokes, and the maximum dE/dt values for 3 leader steps just before return strokes ranged from 30 to 45 V/m/μsec at 100 km. The submicrosecond structures of leader fields have also been measured by C. E. Baum and associates (10,11).

CLOUD PULSES - The overall shapes of the larger radiation field impulses produced by the intracloud discharge processes that initiate cloud-to-ground lightning and also by isolated cloud flashes have been discussed by Weidman and Krider (12) and Beasley, et. al. (13). In general, the shapes of these

*Numbers in parentheses designate References at end of paper.

pulses tend to be bipolar with several fast, unipolar impulses superimposed on the initial half-cycle. The unipolar structures have fast risetimes, and the shapes of the dE/dt signatures during these transitions are very similar to the shapes of the signatures radiated by return strokes. Values of the maximum dE/dt produced by 11 cloud impulses have a mean and standard deviation of 16 ± 8 V/m/μs at 100 km.

FIELD AMPLITUDE SPECTRA - The dE/dt signatures radiated during the fast return stroke transition have been Fourier analyzed to provide field amplitude spectra over the frequency interval from about 1 to 20 MHz. The results for 24 first and 5 subsequent strokes are shown in Figs. 5 and 6, respectively, together with previous spectra published by Serhan, et. al. (14) and Weidman, et. al. (15). Here, the mean spectral amplitudes are given in dB from a reference level of 1 V/m/s, and all data have been range-normalized to 50 km.

Fig. 5 shows three curves; Curve [1] represents the mean spectrum of 24 first stroke signatures that have not been corrected for any truncation of the records at the end of the finite recording interval. In Curve [2], any truncations have been corrected by multiplying the records by a cosine windowing function. Curve [3] shows the mean spectrum of 6 strokes that did not require any truncation correction. Clearly, Curves [2] and [3] are probably the best approximation to the true return stroke source spectrum.

Fig. 6 shows the mean spectrum of 5 subsequent return strokes. Curve [1] is the spectrum of data that have not been corrected for truncation errors, and Curve [2] is the spectrum of the same data after multiplication by a cosine windowing function. Again, Curve [2] is undoubtedly the best approximation to the true subsequent stroke source at the higher frequencies.

DISCUSSION

Lightning current models and the implications that lightning fields have for lightning currents have been discussed by Uman and Krider (1), and by Baum, et. al. (10). If we assume that the initial, fast-rising portions of the fields produced by leaders, return strokes, and cloud impulses can all be described by a form of the transmission line model (1), then the maximum rate of change of the source current is related to the maximum field derivative through the relation:

$$\frac{dI(t)}{dt} = \frac{2\pi D c^2}{v} \frac{dE(t+D/c)}{dt}$$

where D is the range to the discharge, v is the velocity of the current pulse, and where the ground has been assumed to be flat and perfectly conducting. This relation also assumes that the measured field is produced by a single current pulse propagating in a single channel.

Fig. 7 shows a cumulative distribution of the maximum dI/dt values that have been computed for return strokes using the above equation and the field derivatives plotted in Figs. 3 and 4. The values are plotted for a velocity of 10^8 m/s, and the dashed lines show velocities of 0.6 X 10^8 m/s and 1.4 X 10^8 m/s. Fig. 7 also shows the maximum current derivatives measured during lightning strikes to instrumented towers by K. Berger in Switzerland, as reported by Anderson and Eriksson (16), and by Garbagnati, et. al. (17) in Italy. Fig. 8 shows estimates of the maximum dI/dt in leader steps that occur just prior to a return stroke and in the fast structures on cloud impulses.

It should be noted that the maximum current derivatives that are inferred from the E and dE/dt data in Figs. 3 and 4 tend to be substantially higher than those in the tower data. This might be because the towers, which are located on mountains of rock, or the upward connective leaders which originate from the towers, limit the maximum rate of rise of current that can be measured. Another reason might be that the E and dE/dt data have been obtained with a triggered oscilloscope recording system that may not have recorded all of the smaller signatures, and this might have biased the statistics toward larger values. Finally, if the fast field transitions are produced by more than one current pulse radiating simultaneously, then our inferred dI/dt values will overestimate the true value for one pulse. Since the dI/dt values in Figs. 7 and 8 are larger than the dI/dt used in most lightning test standards, we think these problems clearly warrant further study.

ACKNOWLEDGEMENT

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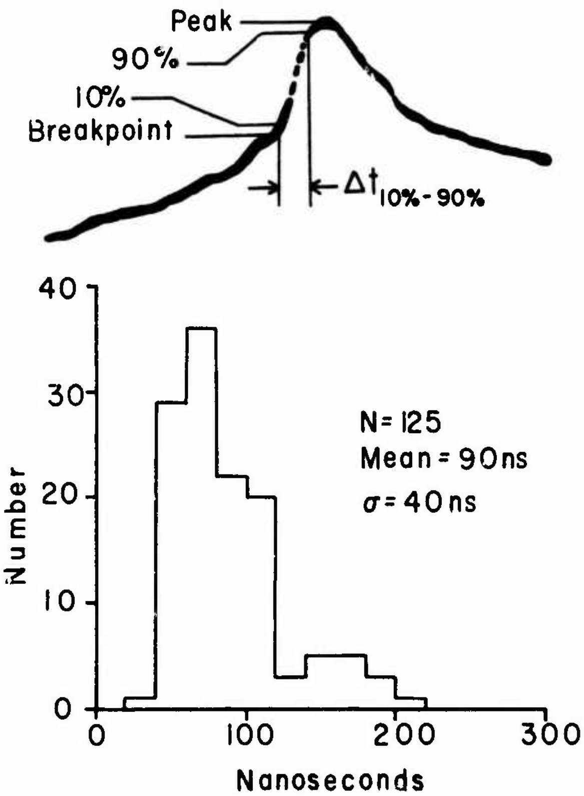

Fig. 1 - A histogram of the 10 to 90% risetime of the fast transition in return stroke E fields

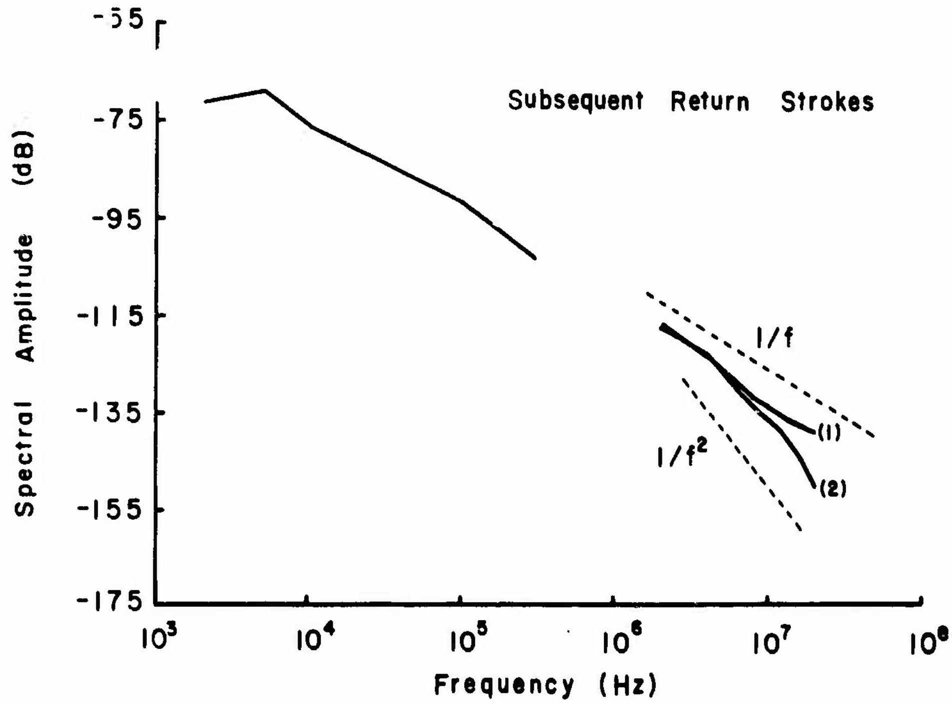

Fig. 6 - The mean amplitude spectrum of 5 subsequent return strokes range-normalized to 50 km. Curve [2] is the best approximation of the true source

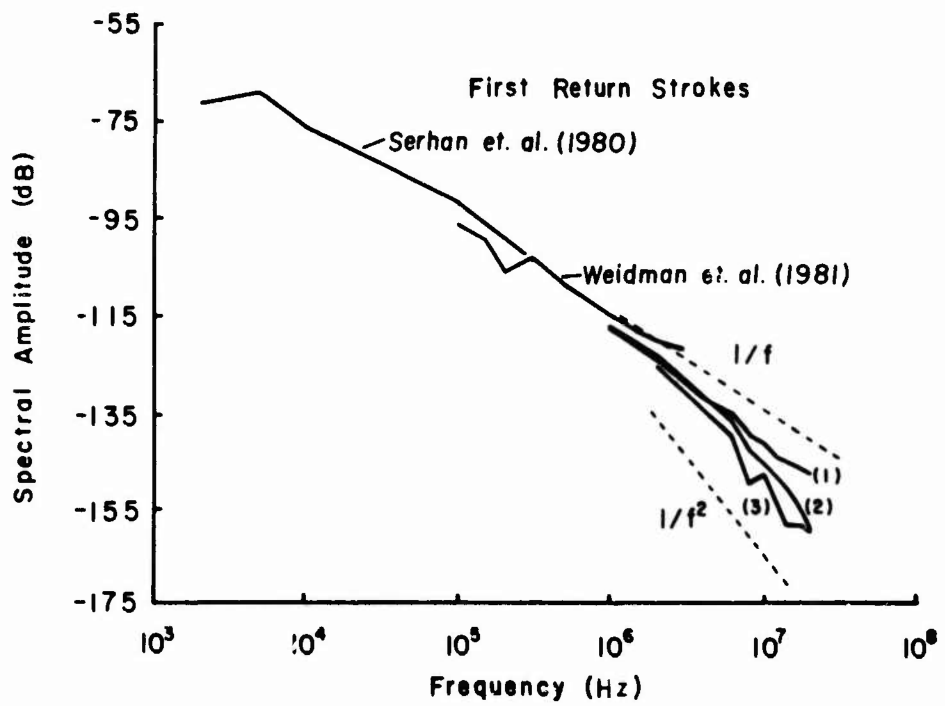

Fig. 5 - The mean amplitude spectrum of 24 first return strokes range-normalized to 50 km. Curves [2] and [3] are the best approximation to the true source at higher frequencies

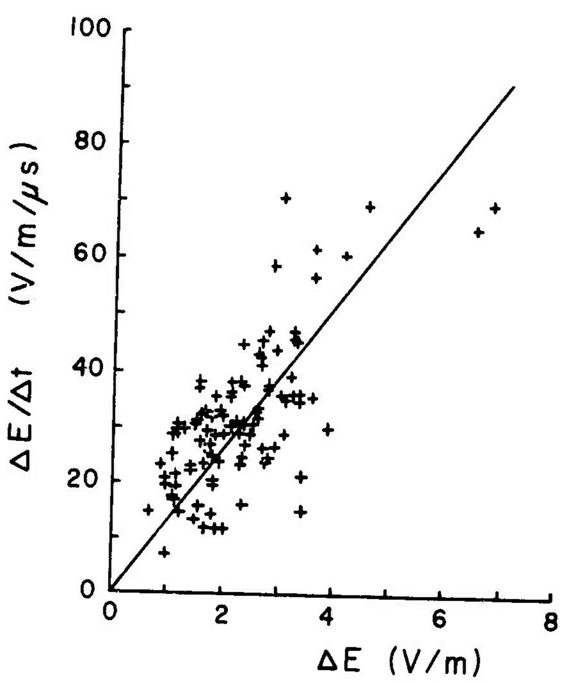

Fig. 3 - A histogram of the maximum rate of rise of the fast transition in return stroke E fields range-normalized to 100 km

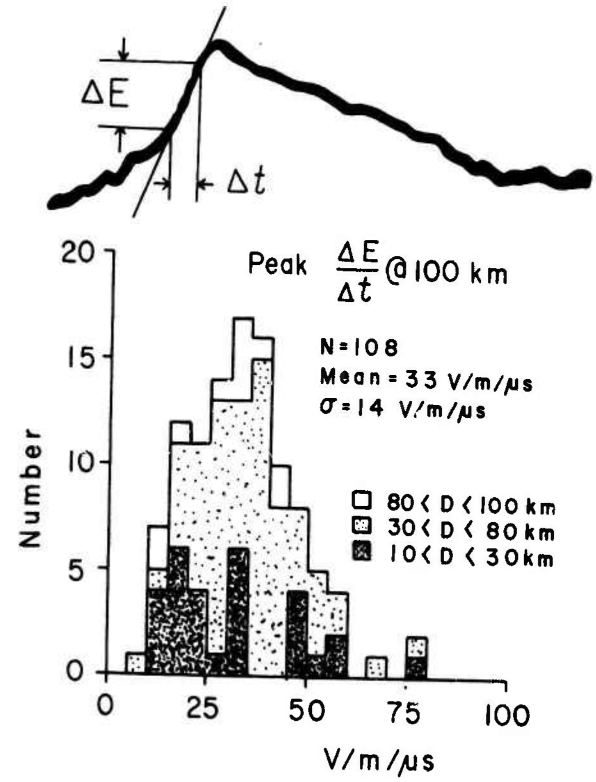

Fig. 4 - Maximum $\Delta E/\Delta t$ during return strokes vs. the associated ΔE

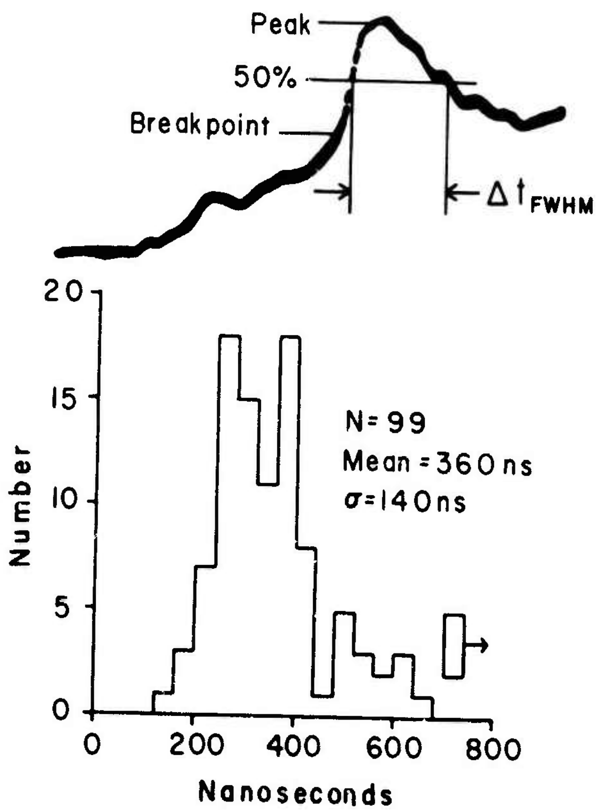

Fig. 2 - Histogram of the full width at half maximum of the fast peak in return stroke E fields

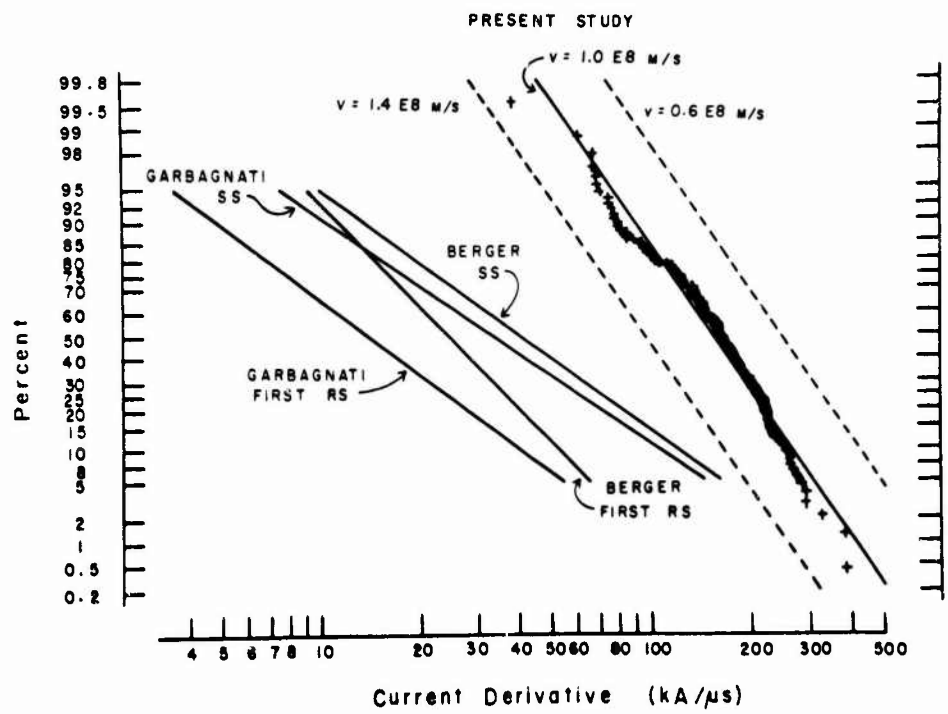

Fig. 7 - Cumulative distribution of the maximum dI/dt during lightning return strokes derived from measured dE/dt fields

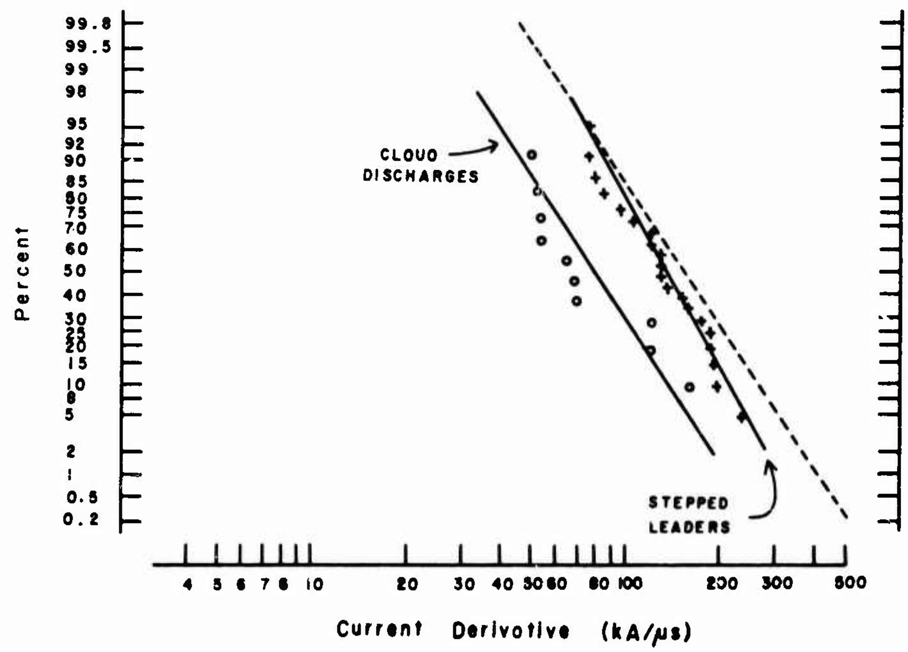

Fig. 8 - Cumulative distribution of the maximum dI/dt during leader steps and the fast components of cloud impulses. These data assume the current propagates at a speed of 10^8 m/s